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Effect of biodiesel from various feedstocks on combustion characteristics, engine durability and materials compatibility: A review

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ABSTRACT

The global energy consumption is expected to grow in a faster rate than the population growth. By 2030, an increase of 53% of global energy consumption and 39% of greenhouse gases emissions from fossil fuels is anticipated. Therefore, it becomes a global agenda to develop clean alternative fuels which are domestically available, environmentally acceptable and technically feasible. As an alternative fuel, biodiesel seems as one of the best choices among other sources due to its environment friendly behavior and similar functional properties with diesel. The main objective of this paper is to discuss the impact biodiesel from different edible, non-edible and waste cooking oils feedstocks on combustion characteristics, engine durability and materials compatibility with biodiesel. Moreover, this paper reviews some other important related aspects to biodiesel such as biodiesel development, biodiesel feedstocks, biodiesel standards and advantages and challenges of biodiesel.

Contents

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1. Introduction

It is well known that in modern economics, energy has the main role in the advancement of all sectors including agricultural, transportation, telecommunication and industrial sectors. As a result, worldwide energy consumption is expected to grow in a faster rate than the population growth [1]. According to the International Energy Agency (IEA), an anticipated increase of 53% of global energy consumption is foreseen by 2030. Energy consumption mostly comes from fossil fuels which account for 87% among other energy sources in which crude oil consisting of 33.06%, coal 30.34% and natural gas 23.67%, respectively. This is primarily due to their adaptability, high combustion efficiency, availability, reliability as well as the handling facilities [2]. The share of nuclear energy, hydropower and renewable energy are very small with only 4.88%, 6.44% and 1.58 of total energy usages, respectively. The world primary fuel consumption has grown from 6630 million tons of oil equivalent (Mtoe) in 1980 to almost double 12,274.6 Mtoe in 2011 as shown in Table 1 [3].

Emissions which are produced from burning petroleum derived fuels have a serious effect on both the environment and human health [4–6]. It is predicted that the greenhouse gases (GHG) emissions from fossil fuels will increase by 39% in 2030 if no enormous effort is done to alleviate it. Numerous factors such as worldwide environmental concerns, price hiking of the petroleum products as well as the expected depletion of fossil diesel fuel have encouraged to look over the clean combustion of diesel engines using alternative fuel sources [7–10].

Therefore, it becomes a global agenda to develop clean alternative fuels which are domestically available, environmentally acceptable and technically feasible. According to the Energy Policy Act of 1992 (EPACT, US), natural gas, biodiesel, ethanol, electricity and methanol are the main prospective alternative fuels that can reduce global warming, fossil fuels consumption and exhaust emissions [4,11]. As an alternative fuel, biodiesel is one of the best choices among others due to its environment friendly behavior and similar functional properties with diesel fuel. Using biodiesel in internal combustion engines can play a great role in reducing fossil fuel demand, environmental impact and the adverse effect on human health [12–16].

However, using straight vegetable oils in engine may cause various engine problems such as injectors coking, carbon deposits on piston and head of engine and excessive engine wear [17]. For this reason it has been recommended by many researchers to transesterify vegetable oils to reduce the high viscosity of the oil. This transesterified vegetable oil is known as biodiesel or fatty acid methyl esters (FAME). Biodiesel is renewable and can be produced from edible and non-edible oil, recycled waste oils and animal fats by transesterification process [18–23].

Table 1
Global primary energy consumptions in 1980, 2010 and 2011 [2].

Source	1980		2010		2011	
	Mtoe	Share (%)	Mtoe	Share (%)	Mtoe	Share (%)
Oil	2979.8	44.9	4031.9	33.66	4059.1	33.06
Natural gas	1296.8	27.3	2843.1	23.73	2905.6	23.67
Coal	1807.9	19.6	3532.0	29.48	3724.3	30.34
Nuclear	161.0	2.4	626.3	5.22	599.3	4.88
Hydropower	384.3	5.8	778.9	6.50	791.5	6.44
Renewable	–	–	165.5	1.38	194.8	1.58
Total	**6629.8**	**100**	**11,977.8**	**100**	**12,274.6**	**100**

1.1. Objective of this paper

Although there is a large number of literatures and researches on engine performances, combustion and emissions characteristics using biodiesel, especially in the last decades, only fewer people have analyzed and reviewed them [24]. This paper presents the potential of biodiesel from different sources and its impact on combustion characteristics including details of engine and operating condition. Moreover, engine durability and materials compatibility with biodiesel have also been covered in this paper. A large number of literatures from highly rated journals in scientific indexes are reviewed including most recent publications.

2. Background of biodiesel development

Biodiesel which is known as fatty acid methyl ester is produced from vegetable oils or animal fats using transesterification process in the presence or absence of catalyst. Biodiesel is non-explosive, biodegradable, non-flammable, renewable, and non-toxic as well as environment friendly [19,23,25]. This fuel has almost similar properties (such as cetane number, energy content, and viscosity and phase changes) with diesel fuel [26]. The major advantages of biodiesel are it can be blended with diesel fuel at any proportion and can be used in a diesel engine without any modification [27]. Moreover, it does not contain any harmful substances and produce less harmful emission to the environment.

In fact, Rudolph diesel has used vegetable oil (peanut oil) as a fuel in a diesel engine in August 10, 1893 [17]. Nonetheless, the conversion of vegetable oil into methyl ester employing the transesterification process was firstly conducted by E. Duffy and J. Patrick in 1853. In 1937, a patent “Procedure for the transformation of vegetable oils for their uses as fuels” from a Belgian scientist, named G. Chavanne was allowed and the concept of biodiesel was proposed for the first time [28]. In 1977, Expedito Parente, a Brazilian scientist, had applied for the first patent of “industrial process for biodiesel”. In the meantime, in South Africa and in 1979, research on biodiesel from sunflower oil was started. The engine-tested biodiesel was completed and it was published globally in 1983. The first pilot plant for biodiesel production was

established in 1987 and the first industrial scales plant was established in 1989 by an Austrian company, Gaskoks. In the late 1990s, the increasing concerns about the environment sustainability and decreasing cost differential had motivated the commercial production of biodiesel. At that time many biodiesel plants were established in European countries. For instance, France produced biodiesel from rapeseed oil which is known locally as 'diester'. Table 2 [29] shows the detailed key milestone of the development of biodiesel industries.

To strength the quality control demand of engine manufacturers for using biodiesel fuel, a number of international standards such as ASTM D6751 (USA and Canada), DIN 51606 (Germany), EN 14214 (Europe) were issued. The present versions of biodiesel fuel standards (EN 14214 and ASTM D6751) were released in 2008 which have replaced all previous standards.

3. Biodiesel feedstocks

One of the main reasons that make biodiesel production more convenient as an energy substitute is the accessibility of biodiesel feedstocks worldwide. The nature of biodiesel feedstocks differs from one location to other depending on their husbandry and geographical locations. There are more than 350 potential oil-bearing crops, among which *Jatropha curcas*, rapeseed, soybean, palm, sunflower, safflower, cottonseed and peanut oils are regarded as potential alternative feedstocks [30,31]. However, some other non-edible oils such as *Calophyllum inophyllum*, *Moringa oleifera*, *Sterculia foetida*, *Madhuca indica* (*Mahua*), *Croton megalocarpus and Pongamia pinnata* are winning worldwide attention. It is very important that any potential feedstock for biodiesel production should be attainable at the lowest price and in an abundant compared to diesel in the competitive market. Generally, feedstocks have been divided into four main categories as follows [8,32–37]:

(a) Edible vegetable oil: rapeseed, soybean, sunflower, palm and coconut oil.
(b) Non-edible vegetable oil: *Jatropha curcas*, *Pongamia pinnata*, sea mango and algae.
(c) Waste or recycled oil.
(d) Animal fats-tallow, yellow grease and chicken fat.

Among other properties of biodiesel feedstock, favorable fatty acid composition, high oil content, low agriculture inputs (water, fertilizers, soils and pesticides), controllable growth and harvesting season, consistent seeds maturity rates and potential market for agricultural by-products are extremely desirable [1,38]. The percentage and type of fatty acids composition rely mainly on the plant species and their growth conditions. Fatty acid compositions of common biodiesel feedstocks are shown in Table 3 [29,37,39–42].

4. Major physic-chemical properties of potential crude edible and non-edible feedstocks

The assessment of the physical and chemical properties of biodiesel feedstocks is very imperative to evaluate their viability for biodiesel production. Table 4 [34] shows the physical and chemical properties of potential edible and non-edible feedstocks. These feedstocks include crude *Calophyllum inophyllum* L. (CCIO), *Jatropha curcas* L. (CJCO), *Sterculia foetida* L. (CSFO), *Croton megalocarpus* L. (CCMO), *Moringa oleifera* L. (CMOO), Coconut (CCO), Palm (CPaO), Canola (CCaO) and Soybean (CSO) oils.

5. Biodiesel conversion processes

Vegetable oil cannot be used directly in diesel engines due to their higher viscosity, low volatility and polyunsaturated characteristics [43]. Therefore, vegetable oils must be refined to turn into quality fuel. The problems of using vegetable oil can be overwhelmed by four methods: pyrolysis, dilution with hydrocarbons blending, micro-emulsion, and transesterification [44–46]. Table 5 [29,47] shows the comparison of biodiesel production technologies. Among the four processes, transesterification process is the most assuring and conventional process to reduce the viscosity and to overcome the high viscosity problem. Moreover, the lower cost and higher conversion efficiency make transesterification technique is widely used for industrialized biodiesel production [31,44,48]. By employing this process the viscosity of vegetable oil can be reduced to a significant level and heat values of the fuel can be maintained. This chemical process turns the vegetable oils into monoesters and separates out the glycerin as a byproduct. The glycerin dribs to the bottom and the biodiesel drifts on the top of the separation funnel. One hundred pounds of fat or oil are reacted with 10 pounds of a short chain alcohol in the presence of a catalyst to produce 10 pounds of glycerin and 100 pounds of biodiesel. As per the transesterification reaction, 3 mol of methanol were required to react with the vegetable oil. The chemical

Table 2
Key milestone of the biodiesel development industry [29].

Date	Event
August 10, 1893	Rudolf Diesel's prime diesel engine model, which was fueled by peanut oil, ran for the first time in Augsburg, Germany
1900	Rudolf Diesel showed his engine at the world exhibition in Paris, his engine was running on 100% peanut oil
August 31, 1937	A Belgian scientist, G. Chavanne, was granted a patent for a "Procedure for the transformation of vegetable oils for their uses as fuels". The concept of what is known as "biodiesel" today was proposed for the first time
1977	A Brazilian scientist, Expedito Parente, applied for the first patent of the industrial process for biodiesel
1979	Research into the use of transesterified sunflower oil, and refining it to diesel fuel standards, was initiated in South Africa
1983	The process for producing fuel-quality, engine-tested biodiesel was completed and published internationally
November, 1987	An Austrian company, Gaskoks, established the first biodiesel pilot plant
April, 1989	Gaskoks established the first industrial-scale plant
1991	Austria's first biodiesel standard was issued
1997	A German standard, DIN 51606, was formalized
2002	ASTM D6751 was first published
October, 2003	A new Europe-wide biodiesel standard, DIN EN 14214 was published
September, 2005	Minnesota became the first US state to mandate that all diesel fuel sold in the state contain part biodiesel, requiring a content of at least 2% biodiesel
October, 2008	ASTM published new Biodiesel Blend Specifications Standards
November, 2008	The current version of the European Standard EN 14214 was published and supersedes EN 14214:2003

Table 3
Fatty acid profiles of some biodiesel feedstocks [29,37,39–42].

Fatty acid	Molecular weight	Systematic name	Palm	Sunflower	Coconut	Soybean	Rapeseed	Peanut	Jatropha	Cottonseed	Pongamia	Tallow	Lard
Lauric (12:0)	200	Dodecanoic	–	0.5	46.5	–	–	–	0.1	–	–	–	0.4
Myristic (14:0)	228	Tetradecanoic	1	0.2	19.2	0.1	–	0.3	0.1	–	–	–	2.3
Palmitic (16:0)	256	Hexadecanoic	42.8	4.8	9.8	11	3.49	12.3	14.6	28.7	9.8	23.3	29.6
Palmitoleic (16:1)	254	Hexadec-9-enoic	–	0.8	–	0.1	–	–	0.6	–	–	0.1	20
Stearic (18:0)	284	Octadecanoic	4.5	5.7	3	4	0.85	4.6	7.6	0.9	6.2	19.3	20
Oleic (18:1)	282	*cis*-9-Octadecenoic	40.5	20.6	6.9	23.4	64.40	53.6	44.6	13	72.2	42.4	33.2
Linoleic (18:2)	280	*cis*-9-cis-12-Octadecadienoic	10.1	66.2	2.2	53.2	22.30	29	31.9	57.4	11.8	2.9	13.1
Linolenic (18:3)	278	*cis*-9-cis-12	0.2	0.8		7.8	8.23	0.1	0.3	–	–	0.9	1.5
Arachidic (20:0)	312	Eicosanoic	–	0.4	–	0.3	–	–	0.3	–	–	–	
Behenic (22:0)	340	Docosanoic	–	–	–	0.1	–	–	–	–	–	–	
Erucic (22:1)	338	*cis*-13-Docosenoic	–	–	–	–	–	–	–	–	–	–	
Lignoceric (24:0)	368	Tetracosanoic	–	–	–	–	–	–	–	–	–	–	

Table 4
Physico-chemical properties of potential edible and non-edible feedstocks [34].

Sl No.	Property	CCIO	CJCO	CSFO	CMOO	CCMO	CCO	CPaO	CSO	CCaO
1	Kinematic viscosity (mm^2/s) at 40 °C	55.677	48.091	75.913	43.4680	29.8440	27.640	41.932	31.7390	35.706
2	Kinematic viscosity (mm^2/s) at 100 °C	9.5608	9.1039	13.608	9.0256	7.2891	5.9404	8.496	7.6295	8.5180
3	Dynamic viscosity (mpa.s) at 40 °C	51.311	43.543	69.408	38.9970	27.1570	25.123	37.731	28.796	32.286
4	Viscosity Index (VI)	165.4	174.10	184.80	195.20	224.20	168.5	185.0	223.2	213.5
5	Flash point (°C)	236.5	258.5	246.5	263	235	264.5	254.5	280.5	290.5
6	CFPP (°C)	26	21	29	18	10	22	23	13	15
7	Density (g/cm^3) at 15 °C	0.951	0.915	0.937	0.8971[a]	0.9100[a]	0.9089[a]	0.8998[a]	0.9073[a]	0.9042[a]
8	Specific gravity at 15 °C	0.952	0.9157	0.938	N/D	N/D	N/D	N/D	N/D	N/D
9	Acid value (mg KOH/g oil)	41.74	17.63	9.49	8.62	12.07	N/D	N/D	N/D	N/D
10	Calorific value (kJ/kg)	38,511	38,961	39,793	N/D	N/D	37,806	39,867	39,579	39,751
11	Copper strip corrosion (3 h at 50 °C)	1a	1a	1a	1a	1a	1a	1a	1a	1a
12	Refractive Index	1.4784	1.4652	1.4651	1.4661	1.4741	1.4545	1.4642	1.4725	1.471
13	Transmission (%*T*)	34.7	61.8	26.6	69.2	87.5	91.2	63.2	65.2	62.9
14	Absorbance (abs)	0.46	0.209	0.574	0.16	0.058	0.04	0.199	0.186	0.202
15	Oxidation stability (h at 110 °C)	0.23	0.32	0.15	41.75	0.14	6.93	0.08	6.09	5.64

CCCI, crude *Calophyllum inophyllum* L. oil; CJCO, crude *Jatropha curcas* L. oil; CSFO, crude *Sterculia foetida* L. oil; CMOO, crude *Moringa oleifera* L. oil; CCMO, crude *Croton megalocarpus* L. oil; CCO, crude coconut oil; CPaO, crude palm oil; CSO, crude soybean oil; CCaO, crude canola oil.

[a] At 40 °C.

reaction of the transesterification process is shown in Fig. 1 [1,49]. Generally, the transesterification process is influenced by different factors [50–57] depending on the condition of the reaction. Those factors include FFA of the vegetable oil, alcohol type and molar ratio, type of the catalyst and the catalyst concentration, temperature of the reaction and time of the reaction, stirring rate, purification of the final product, etc.

In the transesterification process methanol and ethanol are used as alcohol because they are less expensive. Apart from this some other alcohols (propanol, isopropanol, *tert*-butanol, octanol and butanol) can be also used, however, they are expensive [46,58–61]. The basic flow diagram of biodiesel production is shown in Fig. 2 [1]. Detailed classification of transesterification process has been shown in Fig. 3 [17,48].

6. Standards and characterization of biodiesel

Quality standards for producing, marketing and storing of biofuel are being developed and implemented around the world in order to maintain the end product quality and also to ensure the consumers' confidence. Austria was the first country to have defined and approved the standards for biodiesel from rapeseed oil as a petro diesel fuel. At present the US and EU standards are the most referred standards followed by standards from other biofuel producing nations [18]. A comparison of biodiesel standards was shown in Table 6 [10,47,62,63].

7. Major physico-chemical properties of biodiesel from different feedstocks

The properties of biodiesel are characterized by physico-chemical properties such as density, viscosity, flash point, cetane number, oxidation stability, water content, sulfur content, cloud point, pour point, acid value, cold filter plugging point, Conradson carbon residue, lubricity, etc. Tables 7 [10] and 8 [10] show the main characteristics of biodiesel from both edible as well as non-edible oil source.

Table 5
Comparison of biodiesel production processes [29,47].

Technologies	Advantages	Disadvantage
Dilution or micro-emulsion	• Simple process	• High viscosity • Bad volatility • Bad stability
Pyrolysis	• Simple process • No-polluting	• High temperature is required • Equipment is expensive • Low purity
Transesterification	• Fuel properties is closer to diesel • High conversion efficiency • Low cost • It is suitable for industrialized production	• Low free fatty acid and water content are required (for base catalyst) • Pollutants will be produced because products must be neutralized and washed • Accompanied by side reactions • Difficult reaction products separation
Supercritical methanol	• No catalyst • Short reaction time • High conversion • Good adaptability	• High temperature and pressure are required • Equipment cost is high • High energy consumption

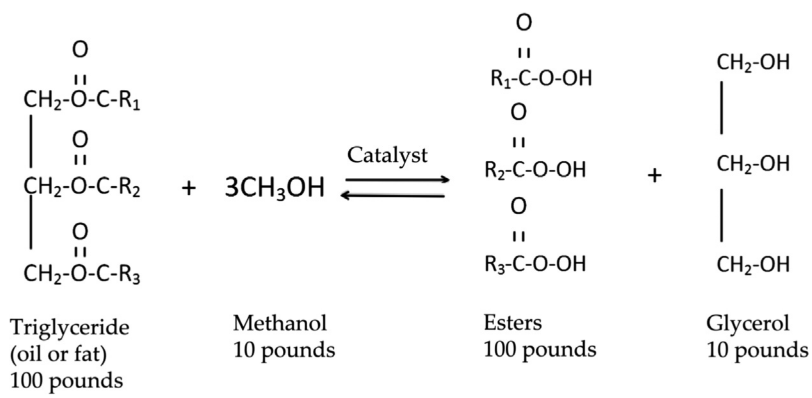

Fig. 1. Chemical reaction of the transesterification process [1,49].

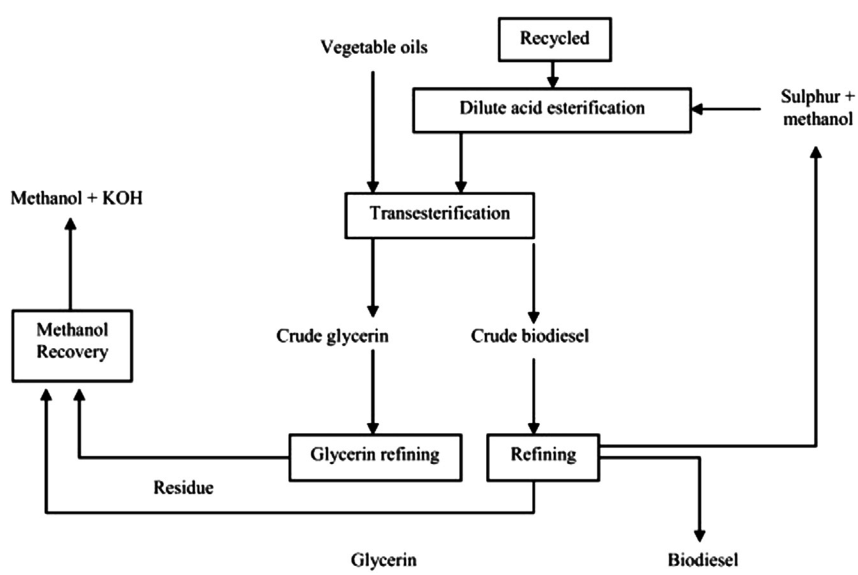

Fig. 2. The basic flow diagram of biodiesel production [1].

8. Advantages and challenges of biodiesel

The main advantages of biodiesel are its portability, renewability, biodegradability, higher combustion efficiency, lower sulfur and aromatic content and higher cetane number. However, biodiesel have some shortcomings also. Most of these problems are eminent and caused catastrophic engine failure when vegetable oil is used. Those problems include carbon deposits on piston, piston rings, valves, engine head and injector tips, filter plugging, injector coking, nozzle blocking, failure of engine lubricating oil, heavy gum and wax formation, deposition on piston, piston rings, injectors and cylinder wall, corrosion of high pressure injecting pump, injectors, injector nozzles, supply or feed pumps, high pressure pipes, elastomers like nitrile rubber softening, swelling,

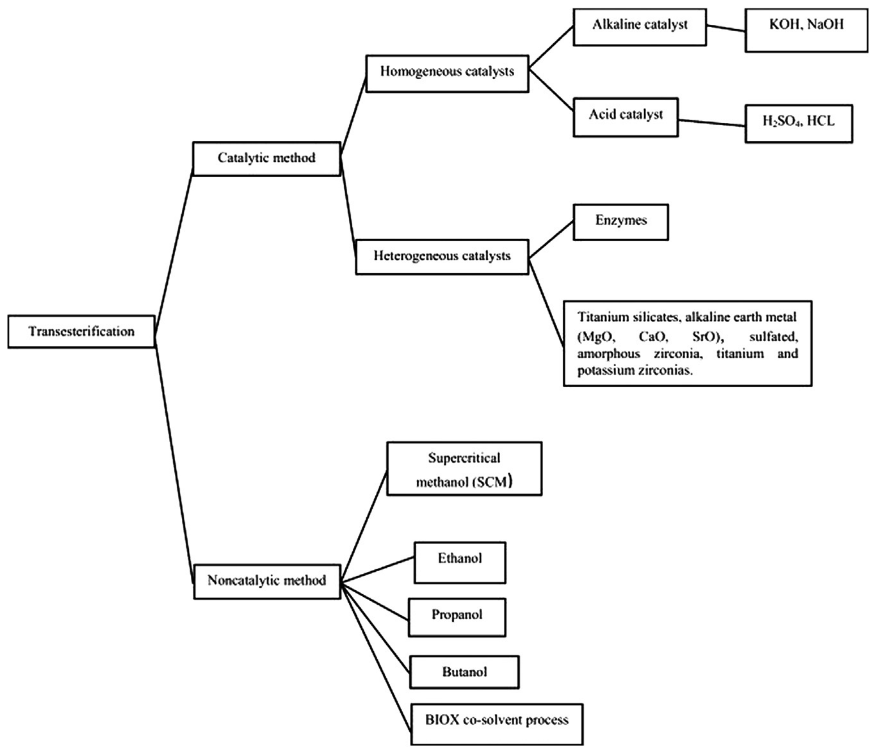

Fig. 3. Details classification of transesterification process [17,48].

Table 6
Comparison of biodiesel Standards around the world [10,47,62,63].

Parameters	Austria (ON)	France (general official)	Germany (DIN)	Italy (UNI)	USA (ASTM)	Malaysia	Korea	Indonesia
Density at 15 °C g/cm^3	0.85–0.89	0.87–0.89	0.875–0.89	0.86–0.90	–	0.8783	0.86–0.89	–
Viscosity at 40 mm^2/s	3.5–5.0	3.5–5.0	3.5–5.0	3.5–5.0	1.9–6.0	4.415	1.9–5.5	2.3–6
Flash point (°C)	100	100	110	100	130	182	> 120	100
Pour point (°C)	–	−10	–	0/−5	–	15	–	
Cetane number	≥ 49	≥ 49	≥ 49	–	≥ 47	56	–	51
Conradson carbon residue (%)	0.05	–	0.05	–	0.05	–	–	–
Iodine number	≤ 120	≤ 115	≤ 115	–	–	58.3	–	–
Methanol/ethanol (mass %)	≤ 0.2	≤ 0.1	≤ 0.3	≤ 0.2	–	< 0.2	< 0.2	–
Ester content (mass %)	–	≥ 96.5	–	≥ 98	–	98.5	96.5	–
Monoglyceride (mass %)	–	≤ 0.8	≤ 0.8	≤ 0.8	–	< 0.4	< 0.8	–
Diglycerides (mass %)	–	≤ 0.2	≤ 0.4	≤ 0.2	–	< 0.2	< 0.2	–
Triglyceride (mass %)	–	≤ 0.2	≤ 0.4	≤ 0.1	–	< 0.1	< 0.2	–
Free glycerides (mass %)	≤ 0.02	≤ 0.02	≤ 0.02	≤ 0.05	≤ 0.02	< 0.01	< 0.02	0.02
Total glycerol (mass %)	≤ 0.24	≤ 0.25	≤ 0.25	–	≤ 0.24	< 0.01	< 0.25	0.24

hardening, cracking. Table 9 [1,46,64–68] shows the main advantages and challenges of biodiesel.

9. Materials compatibility and engine durability using biodiesel

Biodiesel possesses some solvent-like properties. Therefore, biodiesel will have a tendency to dissolve the accumulated particulates and sediments found in diesel storage and engine fuel systems. These dissolved sediments may plug fuel filters or injectors. Biodiesel may also degrade some hoses, gaskets, O-rings, seals elastomers, glues and plastics with prolonged exposure. Plastics, glues and rubber begin to leak and seep as they begin to fail. Older vehicles (manufactured prior to the mid-1990s) are more likely to contain many of the types of materials that would be affected. Table 10 [69,70] show both recommended and non-recommended elastomers and storage tank material.

Durability testing of the engine using biodiesel is very important. However, a few researchers have conducted the engine durability test using biodiesel. In fact some researchers are not focusing on durability test due to some factors such as it is more arduous and expensive than those in engine power, economy and emissions. Table 11 shows the summary of durability test for biodiesel and its blend. For durability studies, the following aspects were focused on: carbon deposit, engine wear and problems in fuel system.

10. Impact of biodiesel on engine combustion characteristics

Various researchers have studied the impact of biodiesel from different sources on engine combustion characteristics. Based on

Table 7
Major physico-chemical properties of biodiesel from edible oil feedstocks [10].

Fuel properties	Diesel fuel	Biodiesel from edible feedstocks										
	ASTM D975	ASTM D6751	EN 14214	Palm FAME	Coconut FAME	Sunflower FAME	Soybean FAME	Peanut FAME	Rapeseed FAME	Safflower FAME	Mustard FAME	Olive FAME
Density 15 °C (kg/m³)	850	880	860–900	864.42	807.3	880	913.8	848.5	882	888.5	931	–
Viscosity at 40 °C (cSt)	2.6	1.9–6.0	3.5–5.0	4.5	2.726	4.439	4.039	4.42	4.439	5.8	6.13	4.5
Cetane number	40–55	Min. 47	Min. 51	54.6	–	49	37.9	53.59	54.4	56	55	57
Iodine number	38.3	–	Max. 120	54	–	–	128–143	67.45	–	–	–	–
Calorific value (MJ/kg)	42–46	–	35	–	–	–	39.76	40.1	37	38.122	43.42	–
Acid value (mg KOH/g)	0.062	Max. 0.50	Max.0.5	0.24	0.106	0.027	0.266	0.28		–	0.37	0.19
Pour point (°C)	−35	−15 to −16	–	15	–	–	2	−8	−12	–	–	–
Flash point (°C)	60–80	Min. 100–170	> 120	135	114.8	160	76	166	170	148	–	178
Cloud point (°C)	−20	−3 to −12	–	16	0	3.4	9	0	−3.3	−5	3.2	0
Cold filter plugging point (°C)	−25	19	Max. +5	12	−4	−3	11	–	−13	–	−5	−6
Copper strip corrosion (3 h at 50 °C)	1	Max. 3	Min.1	1a	1b	1a	1b	–	–	–	1a	1a
Carbon (wt%)	84–87	77	–	–	–	–	–	62.1	81	–	–	–
Hydrogen (wt%)	12–16	12	–	–	–	–	–	–	12	–	–	–
Oxygen (wt%)	0–0.31	11	–	–	–	–	–	–	7	–	–	–
Sulfur % (m/m)	0.05	Max. 0.05	10[b]	0.003	3.2	0.2	0.8	0	–	–	–	1.9
Sulfated ash % (m/m)	–	Max. 0.02	Max. 0.02	0.002	0.006	0.005	0.005	–	–	–	–	0.005
Oxidation stability (h at 110 °C)	–	3	6	10.3	3.55	0.9	2.1	2	7.6	–	–	3.3
Lubricity (HFRR, μm)	685	314	–	172	–	–	–	–	–	–	–	139.5

Table 8
Major physico-chemical properties of biodiesel from non-edible oil feedstocks [10].

Fuel properties	Diesel fuel	Biodiesel from non-edible oil source										
	ASTM D975	ASTM D6751	EN 14214	Tobacco FAME	Neem FAME	Calophyllum FAME	Rubber FAME	Mahua FAME	Beef tallow FAME	Jatropha FAME	Pongamia FAME	Cottonseed FAME
Density 15 °C (kg/m³)	850	880	860–900	888.5	868	888.6	–	874	877	879.5	931	876.7
Viscosity at 40 °C (cSt)	2.6	1.9–6.0	3.5–5.0	4.23	5.213	7.724	5.81	5	4.824	4.8	6.13	4.11
Cetane number	40–55	Min. 47	Min. 51	51.6	–	51.9	–	65	58.8	51.6	55	55
Iodine number	38.3	–	Max. 120	136	–	85	–	–	–	104	–	–
Calorific value (MJ/kg)	42–46	–	35	44.6	39.81	–	36.5	37	8	39.23	43.42	40.430
Acid value (mg KOH/g)	0.062	Max. 0.50	Max. 0.5	0.3	0.649	0.76	–	0.41	0.147	0.4	0.42	0.19
Pour point (°C)	−35	−15 to −16	–	–	2	–	−8	6	9	2	3	6
Flash point (°C)	60–80	Min. 100–170	> 120	165.4	76	151	130	208	150	135	95	153
Cloud point (°C)	−20	−3 to −12	–	–	9	38	4	–	12	2.7	7	7
Cold filter plugging point (°C)	−25	19	Max. +5	−5	11	–	–	–	14	0	–	1
Copper strip corrosion (3 h at 50 °C)	1	Max. 3	Min. 1	1a	1b	1b	–	–	1a	1a		1a
Carbon (wt%)	84–87	77	–	–	–	–	–	–	–	–	–	–
Hydrogen (wt%)	12–16	12	–	–	–	–	–	–	–	–	–	–
Oxygen (wt%)	0–0.31	11	–	–	–	–	–	–	–	–	–	–
Sulfur % (ppm)	0.05	Max. 0.05	10	–	473.8	16	–	164.8	7	1.2	–	1.9
Sulfated ash % (m/m)	–	Max. 0.02	Max. 0.02	0.0004	> 0.005	–	–	–	0.005	0.009	–	0.005
Oxidation stability (h at 110 °C)	–	3	6	0.8	7.1	–	–	–	1.6	3.2	–	1.85
Lubricity (HFRR, μm)	685	314	–	–	–	–	–	–	–	–	–	139.5

the available literature, Table 12 has been prepared to show the work done by various researchers on engine combustion characteristics using biodiesel from different sources as the engine fuel. The next section will discuss some of these studies.

Table 9
Advantages and challenges of biodiesel [1,46,64–68].

Advantages	Challenges
Biodiesel emits fewer emissions such as CO_2, CO, SO_2, PM and HC compared to diesel	It emits higher NO_x emission than diesel
Producing biodiesel is easier than diesel and is less time consuming	Higher pour and cloud point fuel freezing in cold weather causing a cold weather starting
Biodiesel can make the vehicle perform better as it has higher cetane number. Moreover, it prolongs engine life and reduces the need for maintenance (Biodiesel has better lubricating qualities than fossil diesel)	Biodiesel has a corrosive nature against copper and brass
Owing to the clarity and the purity of biodiesel, it can be used without adding additional lubricant unlike diesel engine	The high viscosity (about 11–17 times greater than diesel fuel) due to the large molecular mass and chemical structure of vegetable oils leads to problem in pumping, combustion and atomization in the injector system of a diesel engine
Biodiesel hold a great potential for stimulating sustainable rural development and a solution for energy security issue	Biodiesel lower engine speed and power. The biodiesels on the average decrease power by 5% compared to that of diesel at rated load
Biodiesel is more cost efficient then diesel because it is produced locally	Coking of injectors on piston and head of engine
Biodiesel does not need to be drilled, transported, or refined like diesel	Biodiesel degradation under storage for prolonged periods
Biodiesel is better than diesel fuel in terms of sulfur content, flash point, aromatic content and biodegradability	The high viscosity, in long-term operation introduces the formation of injector deposits, plugging of filters, lines and injectors, ring sticking and incompatibility with conventional lubricating oils. Carbon deposits on piston and head of engine
It is safer to handle, being less toxic, more biodegradable, and having a higher flash point	
Non-flammable and non-toxic, reduces tailpipe emissions, visible smoke and noxious fumes and odors	Biodiesel causes excessive engine wear
No required engine modification up to B20	Biodiesel is not cost-competitive with gasoline or diesel
Higher combustion efficiency. Portability, availability and renewability of biodiesel	Low volatility of biodiesel

Table 10
Recommended and non-recommended elastomer and storage tank materials for biodiesel [69,70].

Recommended for B_{100}	Not Recommended for B_{100}
Teflon	Nitrile
Viton	Buna N
Fluorinated plastics	Natural rubber
Nylon	Polypropylene, polyethylene (long-term exposure will weaken)
Aluminum	Copper, brass, bronze
Carbon, stainless steel	Lead, tin, zinc
Fiberglass (most types)	

Table 11
The summary of durability test for biodiesel and its blend.

Biodiesel	Reference fuel	Engine	Operating condition	Duration	Test result	Reference
100% Waste olive oil methyl ester	Diesel	3-Cylinder, WC, DI, 2.5 L	8–15 kw	50 h	No visual difference of carbon deposits and wear	[71]
100%, 15%, 7.5% palm oil methyl ester	Diesel	4-Cylinder, NA, WC, IDI, 1.8 L	800–3600 rpm	100 h	Wear reduce with increasing biodiesel content	[72]
1%, 2%, 3% water with palm oil	Diesel	1-Cylinder, NA, WC, DI	2700 rpm and 5.5 Nm load	100 h	Lower carbon deposits and higher ash	[73]
20% Rice bran oil methyl ester	Diesel	4-Cylinder, NA, WC, DI	Ten non-stop running cycle	100 h	Lower both carbon deposits and wear	[74]
100% Rapeseed oil methyl ester	Diesel	6-Cylinder WC, DI, 11L	–	110 h	Similar carbon deposit but injector more cleaner than diesel	[75]
0%, 50%, 100% Cotton seed oil	Diesel	Turbocharged diesel engine	–	200 h	More carbon deposit, ash and wear in combustion chamber	[76]
100% Mahua, karanja oil methyl ester	Diesel	–	Immersion test	300 h	No corrosion on piston metal	[77]
20% Linseed oil methyl ester	Diesel	1-Cylinder, WC, portable	1500 rpm	512 h	No filter plugging, lower wear	[78]
20% Linseed oil methyl ester	Diesel	1-Cylinder, WC, portable	1500 rpm	512 h	Lower wear	[79]
100%, 50% soybean oil methyl ester	Diesel	TC, DI, 1.9 L	NEDC driving cycle	1350 and 750 Km	Higher wear except piston	[80]
100% Soy methyl ester	Diesel	1-Cylinder DI	25–100% load	1000 h	Small amount injector deposit	[81]
100% Castor methyl ester	Diesel	1-Cylinder DI	25–100% load	1000 h	Normal wear rate	[81]
50% Rubber seed oil	Diesel	1-Cylinder, NA, WC, DI	1500 rpm, no load and full load	10 h	Large carbon deposit on injector, piston head	[82]
Palm oil	Diesel	1-Cylinder, NA, WC, DI	1800 rpm	350 h	Higher deposit on cylinder head	[83]

WC, water cooled; NA, natural aspirated; IDI, indirect injection.

Table 12
Work done by various researchers on engine combustion characteristics using biodiesel from different sources as the engine fuel.

Biodiesel feedstock	Ref. fuel	Engine	Operating condition	Combustion results	References
Paradise oil	Diesel	1-Cylinder, 4-stroke, DI, AC	Full load, 1500 rpm	Higher CP, higher HRR	[84]
Paradise oil	Diesel	1-Cylinder, 4-stroke, AC, DI	1500 rpm	Lower CP, lower HRR	[85]
Jatropha oil	Diesel	1-Cylinder, AC, DI,	Different load conditions and 1500 rpm	Lower CP and lower HRR	[86]
Pongamia oil	Diesel	1-Cylinder, 4-stroke, WC, DI, vertical diesel engine	At constant speed (1500 rpm)	Lower CP, lower HRR	[87]
Algae oil	Diesel	1-Cylinder, IDI, NA	Different engine speeds and injection timing	Higher CP, higher HRR	[88]
Jojoba oil	Gas oil	1-Cylinder, IDI, 4-stroke, NA	Different load, speeds and injection timing	Higher CP	[89]
Croton megalocarpus oil	Diesel	DI, 4-cylinder, turbocharged	Constant speed (3000 rpm) and different load conditions	Higher CP, higher HRR	[90]
Karanja oil	Neat biodiesel	4-Cylinder, turbocharged, DI, forced circulation cooling	Different loads, constant speed of 16.67 s^{-1}	Lower CP at full load whereas primarily higher, lower energy release rate	[91]
Neem oil	Diesel	Vertical, 4-stroke, 1-cylinder, DI, WC	Constant speed 1500 rpm, fuel injection pressure range: 200–205 bar	Higher CP, identical HRR	[92]
Koroch oil	Diesel	1-Cylinder, 4-stroke, NA, DI, WC	Various load conditions	More or less same CP, higher HRR	[93]
Crude rice bran oil	Diesel	DI, AC	Various load condition	Lower CP, initially HRR lower but near to TDC higher HRR	[94]
Palm oil	Diesel	4-Stroke, DI, NA, WC, 1-cylinder	Full load condition	Higher CP and lower HRR	[95]
Soybean oil	Diesel	1-Cylinder, NA, 4-stroke, WC, DI	Full load, 1500 r/min	Higher CP and lower HRR	[97]
Soybean oil	Diesel	6-Cylinder, 4-stroke, DI	Full load condition	Not mentioned	[98]
Soybean oil	Diesel	4-Cylinder, turbocharged, DI	Full load at 1400 rpm	NA	[99]
Linseed oil	Diesel	1-Cylinder 4-stroke, AC	1500 rpm, fuel IP: 200, 220 and 240 bar	Higher CP	[100]
Canola oil	Diesel	1-Cylinder, 4-stroke, NA, AC, DI	Different IP, speed constant and different loads	Lower CP, lower HRR	[101]
Neat rapeseed oil	Diesel	6-Cylinder, DI, turbocharged, 4-stroke	Variable engine speed and full load conditions	Lower CP, lower HRR	[102]
Waste plastic oil	Diesel	1-Cylinder, 4-stroke, CI, AC, DI	Constant speed, various injection timings	Higher CP	[103]
Canola oil	Diesel	6-Cylinder, WC, DI, NA, 4-stroke	1500 rpm, full load	Higher CP	[104]
Waste cooking oil	Diesel	1-Cylinder, 4-stroke, WC	1500 rpm (constant), 50% load	Higher CP, lower HRR	[105]

CP, cylinder pressure; HRR, heat release rate; TDC, top dead center; NA, natural aspirated; AC, air cooled; WC, water cooled; DI, direct injection; IP, injection pressure.

10.1. Impact of biodiesel from non-edible oil feedstocks on engine combustion characteristics

10.1.1. Paradise oil

Devan et al. [84] studied the combustion characteristics of a diesel engine using different blends of paradise oil methyl ester (ME) and eucalyptus oil (EU) in a naturally aspirated single cylinder four-stroke DI diesel engine. The main findings of the study show that high eucalyptus oil blends provide higher cylinder pressure compared to that of diesel at different crank angles and loads (0–100% load). However, the increase in the methyl ester of paradise oil decreases the peak pressure and hence ignition delay. The results of heat release rate at 100% load show that the heat release rate for diesel is the lowest among all the tested fuels. The increase in the concentration of eucalyptus oil in the blend increases the heat release rate. This is mainly attributed to the lower cetane number and longer ignition delay of eucalyptus oil. It was concluded that the cylinder pressure and heat release pattern of ME50-Eu50 blend are found closer to that of standard diesel fuel.

Devan and Mahalakshmi [85] studied the combustion characteristics of paradise oil methyl ester (MEPS) and its blends with diesel in a single cylinder four-stroke air-cooled diesel engine. The main test results showed that the peak cylinder pressure for all methyl ester blends at all engine loads is lower than diesel. This is because the combustion starts earlier for methyl ester blends than for diesel due to the advance injection timing (because of the higher density of biodiesel). It is observed that the ignition delays of MEPS and its diesel blends are lower than that of diesel and are decreasing with an increase in the % MEPS in the blend. As a result of the high in-cylinder temperature existing during fuel injection, biodiesel may undergo thermal cracking; as a result of this, lighter compounds are produced, which might have ignited earlier, resulting in a shorter ignition delay. It has also been observed that as the percentage of MEPS in the blend increases, the maximum heat release rate decreases compared to that of diesel. This is due to the lower heating value of the methyl ester blend.

10.1.2. Jatropha oil

Chauhan et al. [86] studied the combustion characteristics of Jatropha biodiesel (JME100) in a diesel engine and compared with diesel fuel. The results showed that Jatropha biodiesel has lower peak cylinder pressure and lower heat release rate compared to diesel fuel. Moreover, premixed combustion heat release is higher for diesel, which is responsible for higher peak pressure and higher rate of pressure rise in comparison to Jatropha biodiesel. This is attributed to the higher cetane number of Jatropha biodiesel resulting in shorter ignition delay and more fuel burnt in diffusion stage.

10.1.3. Pongamia oil

Jaichandar et al. [87] aimed to optimize the combination of injection timing and combustion chamber geometry of 20% Pongamia oil methyl ester (POME) by volume blend (B_{20}) in a diesel engine. The main findings of the test showed that B_{20} has a slightly lower peak cylinder pressure compared to diesel fuel. The authors attributed that to the improper mixing of B_{20} with air due to higher viscosity and lower calorific value for B_{20}. Moreover, the ignition delay for B_{20} is significantly lower than that of diesel fuel due to the higher cetane number of B_{20}. In case of maximum heat release rate B_{20} gives lower heat release rate than that of diesel fuel due to the shorter ignition delay and poor atomization. It has been observed that for all test fuels and combustion chamber geometries the reduction in ignition delay increases with the increase in load. This may be due to higher combustion chamber wall temperature and

reduced exhaust gas dilution at higher loads. It was also found that retarding the injection timing lowers marginally ignition delay, peak in-cylinder temperature and maximum heat release rate and thereby reduces NO_x emission. Finally, it has been found that toroidal re-entrant combustion chamber (TRCC) geometry with B_{20} has shown maximum peak pressure and maximum heat release rate compared to baseline engine operated with diesel fuel.

10.1.4. Algae oil

Haik et al. [88] studied the combustion characteristics of algae methyl ester and its blends with diesel (10% and 20%) in an indirect injection Ricardo E6 diesel engine. The effects of engine speed, engine load, injection timing and engine compression ratio on the maximum pressure rise rate, maximum combustion pressure and maximum heat release rate were studied. The results showed that the algae oil ME exhibits the highest combustion pressure rise rate compared to algae oil and diesel. Algae oil ME produces slightly higher heat release rate than the diesel. This small increase may be due to the late combustion of the algae oil ME with its increased delay period compared to diesel fuel which produces very fast combustion with respect to time. For the algae oil ME, the increase in combustion noise and decrease in output torque can be improved by retarding the injection timing. It has been found that advancing the fuel injection process increases the maximum pressure rise rate. This increase is due to the increased delay period for the fuels as the pressure/temperature at the onset of injection is becoming less with more the advanced injection. It has also been observed that decreasing the engine compression ratio from 22 to 18 caused the maximum pressure rise rate to increase slightly.

10.1.5. Jojoba oil

Selim et al. [89] studied the combustion characteristics of an indirect Ricardo E6 compression swirl diesel engine using biodiesel from Jojoba methyl ester (JME) and its blend (B_{25}, B_{50} and B_{75}). The authors studied the effects of engine speed (1000–200 rpm), load (0.5–21 Nm), injection timing (20–45° BTDC), and compression ratio (22 and 18) on maximum combustion pressure and maximum pressure rise rate. Additional tests have been carried out for pure diesel and pure JME to check the cyclic variability of maximum pressure and maximum pressure rise rate. The main finding of this study indicates that the pressures and pressure rise rates for pure JME are almost similar to those of gas oil. However, JME exhibits slightly lower pressure rise rate than gas oil which may be attributed to the slightly increased heating value of the JME. This appears to be advantageous with the new fuel. The maximum pressure rise rate for JME is similar to that of pure gas oil at the middle range of injection timing, e.g. from 25° to 35° BTDC. However, for very early injection, 45°, or very late injection, 20°, the JME produced higher rate of pressure rise.

10.1.6. Croton megalocarpus oil

Kivevele et al. [90] studied the effects of antioxidants on the combustion characteristics of a four cylinder turbocharged direct injection (TDI) diesel engine fueled with Croton megalocarpus biodiesel. In general, it has been observed that the cylinder peak pressure and heat release rate increased with the increase in load. At no load condition (0% load), no significant differences in peak cylinder pressure were observed among all four fuel samples tested. However, at full load condition (100% load), it was observed that the maximum peak cylinder pressure was established with the B_{100}, $B_{100+PY1000}$ and B_{20} compared to diesel (D_2) which recorded slightly lower peak cylinder pressure. The heat release rates of biodiesel samples were found to be slightly higher than for mineral diesel at all loads except at full load where diesel fuel recorded a maximum heat release together with B_{100} and $B_{100+PY1000}$ samples. It was also observed that the cylinder pressure and heat release rate for treated (B_{100}) and untreated ($B_{100+PY1000}$) biodiesel were similar. Therefore, it can be concluded that the combustion characteristics of B_{100} were not influenced by the addition of PY antioxidant.

10.1.7. Karanja oil

Anand et al. [91] studied the combustion characteristics of karanja biodiesel and its blend with methanol in a turbocharged, direct injection, multi-cylinder truck diesel engine at different load conditions and constant speed without altering injection timings. The min results of the experimental investigation indicate that the ignition delay, the maximum rate of pressure rise and energy release rates increase at all the loads. However, the peak pressure and the peak energy release rate decrease significantly at higher load conditions while the changes are insignificant at lower loads. Compared to neat biodiesel, it was observed that the ignition delay for biodiesel–methanol blend is slightly higher and the maximum increase is limited to 1° CA. At no load condition, it was observed that the cylinder pressure trends of biodiesel–methanol blend and neat biodiesel are similar. Whereas at full load condition, there is a decrease in cylinder pressure with biodiesel–methanol blend operation. This is because of the lower cylinder gas temperature on account of higher latent heat of vaporization and higher specific heat as well as due to lower heat of reaction of the blend compared to neat biodiesel. The results of energy release rates indicate that the addition of methanol to biodiesel has not resulted in any change in energy release rate at no load condition, whereas the peak energy release rate decreases at full load for the blend compared to neat biodiesel due to its lower energy content.

10.1.8. Neem oil

Dhar et al. [92] studied the combustion characteristics of neem oil biodiesel and it blends (B_5, B_{10}, B_{20} and B_{50}) in a direct injection (DI) diesel engine at various engine loads. In this study, various combustion parameters such as pressure–crank angle history, rate of cylinder pressure rise, heat release rate, cumulative heat release and mass fraction burned were analyzed. The results of the maximum cylinder pressure at different loads showed that at all loads, the peak pressure for B_{20} is higher than mineral diesel. Peak pressure for B_5 and B_{10} is significantly lower than mineral diesel. The peak pressure for B_{20} is higher because of the shorter ignition delay and fast burning of the accumulated fuel as a consequence of optimum oxygen content in the fuel and comparatively lower viscosity due to small concentration of biodiesel in the fuel. The authors also reported that the combustion started earlier for higher biodiesel blends, however, start of combustion was slightly delayed for lower biodiesel blends in comparison to mineral diesel. The rate of heat release trends for all the biodiesel blends was almost identical to mineral diesel.

10.1.9. Koroch oil

Gogoi et al. [93] compared the combustion characteristics of koroch oil methyl ester (KSOME) blends (B_{10}–B_{40}) with diesel in a small direct injection (DI) diesel engine at different load conditions. The main finding of this study showed that engine combustion parameters such as pressure crank angle diagram, peak pressure, time of occurrence of peak pressure, net heat release rate, cumulative heat release, ignition delay and combustion duration indicate that (KSOME) blends exhibited almost similar combustion trend with diesel. It has been observed that early pressure rise and heat release rates were observed in case of the (KSOME) blends at all loads. This is attributed to the early premixed combustion and shorter ignition delay of the blends.

The peak pressure of the combustion gases with diesel and the KSOME blends was more or less the same at full load. At other loads, the peak pressure was slightly higher for the blends compared to diesel fuel. As compared to diesel and over the entire range of load, the cumulative heat release was higher for the blends B_{10}, B_{20} and B_{30} and it was significantly less for the blend B_{40}. As a conclusion of this study, the authors recommended that KSOME blending up to 30% with diesel can be used as fuel in the diesel engine.

10.1.10. Rice bran oil

Saravanan et al. [94] studied the combustion characteristics of a diesel engine operated with crude rice bran oil methyl ester (CRBME) blend (B_{20}) in a stationary small duty direct injection (DI) compression ignition (CI) engine. It has been observed that the peak pressure increases with load for both fuels and diesel produces higher peak pressure than that of CRBME blend at all loads. This is due to the lower energy content and shorter delay period of CRBME blend compared to diesel. It was also observed that the delay period for both fuels decreases with increase in load. The delay period for CRBME blend is lower than that of diesel by an average of 10%. This is due to its higher cetane number compared to diesel. As the calorific value of CRBME blend is lower than that of diesel it reduces the heat release rate. The magnitude of the initial peak of the heat release rate and the maximum heat release of CRBME blend is lower compared to diesel due to its shorter delay period (12.9° compared to 14.54° for diesel). They also found that closer to TDC; the magnitude of heat release rate for CRBME blend is higher than that of diesel.

10.2. Impact of biodiesel from edible oil feedstocks on engine combustion characteristics

10.2.1. Palm oil

Sharon et al. [95] studied the combustion characteristics of a palm oil biodiesel and its 25%, 50% and 75% by volume blends at different load conditions and constant speed in DI diesel engine. The results showed that peak pressure of B_{25}, B_{75}, and B_{100} are 1.08 bar, 8.124 bar and 7.347 bar higher than diesel. It has also been observed that biodiesel and their blends showed shorter ignition delay of 2.1°, 1.9°, 1.7° and 1° for B_{100}, B_{75}, B_{50} and B_{25}, respectively compared to diesel fuel. This is because of higher cetane number and the presence of some fatty acids in biodiesel which stimulates easy vaporization hence it would reduce the ignition delay. Maximum heat release rate for B_{25}, B_{50}, B_{75} and B_{100} were 1.343 kJ/m^3 deg, 2.192 kJ/m^3 deg, 13.884 kJ/m^3 deg and 21.149 kJ/m^3 deg, respectively, lower than diesel fuel. This is attributed to the lower ignition delay of biodiesel blended fuel.

Benjumea et al. [96] studied the effect of altitude (500 and 2400 above sea level) on the combustion characteristics of palm biodiesel and compared with diesel fuel (B_0). The test was carried out in high speed direct injection automotive diesel engine operating at 2000 rpm and 100 Nm. The main findings of the study indicate that biodiesel fueling and altitude had an additive effect on the advance in injection and combustion timing as compared to diesel fuel. As altitude increased, biodiesel fueling led to shorter combustion duration, and higher in-cylinder pressures and fuel–air equivalence ratios. Combustion duration increased with altitude for both fuels, but in a greater extent for B_0. This result can be explained as a consequence of the lesser burning rate and higher boiling point of the tested diesel fuel. The authors concluded that palm oil biodiesel fueling can lead to a better engine performance at high altitudes.

10.2.2. Soybean oil

Qi et al. [97] studied the combustion characteristics of soybean oil biodiesel and diesel at different load conditions in a single cylinder, naturally aspirated, four-stroke, water cooled, direct injection, high speed diesel engine with a bowl in piston combustion chamber. The result showed that biodiesel and diesel exhibit different combustion characteristics with the variation of engine loads due to the different properties of both fuels. At lower engine loads, the peak cylinder pressure and the peak rate of pressure rise are slightly higher for biodiesel. At higher engine loads, the peak cylinder pressures for both fuels are almost the same, but the peak rate of pressure rise is lower for biodiesel. Combustion for biodiesel starts earlier owing to a shorter ignition delay and advanced injection time at different engine loads. At lower engine loads, the heat release rate for diesel is slightly lower than that for biodiesel, but at higher engine loads, the heat release rate for diesel is higher because of the longer ignition delay.

Bueno et al. [98] studied the combustion characteristics of a turbocharged diesel engine operated with soybean oil ethyl ester and it is 10%, 20%, and 30% by volume blends at full load conditions. The test results showed that the crank angle interval required to a combustion reaction progresses of 90% presented an average reduction of 1.81 for B_{10}, 1.87 for B_{20} and 1.97 for B_{30} was obtained with relation to diesel. The authors attributed that to the shorter mixing time of neat biodiesel (B_{100}). They also indicated that the initial heat release rates of diesel and B_{20} were very well matched, which indicated that the biodiesel bulk modulus of compressibility, or speed of sound, does not affect the beginning of injection with the engine. Moreover, a reduction in lower in-cylinder mean temperatures was observed for B_{20} blend. This can be attributed to the reduction in fuel heat value and injected mass caused by biodiesel addition to diesel fuel.

Canakci et al. [99] studied the combustion characteristics of a turbocharged DI compression ignition engine fueled with soybean biodiesel and compared it with diesel fuel. The test was performed at full load at 1400-rpm engine speed. The test results showed that the start of fuel injection for the pure soybean biodiesel fuel occurred earlier than the diesel fuel. It has been attributed to the combination of the different physical properties of the fuel and fuel quantity-related changes in the injection pump timing. The ignition delay period for the pure sunflower biodiesel fuel was shorter than for diesel fuels. The combination of earlier injection timing and shorter ignition delay caused the biodiesel fuels to ignite earlier than the diesel fuel.

10.2.3. Linseed oil

Puhan et al. [100] studied the combustion characteristics of linseed biodiesel in a direct injection diesel engine at different injection pressures (200, 220 and 240 bar). The combustion analysis shows that when the injection pressure increases the ignition delay reduces. This may be due to lower sauter mean diameter, shorter breakup length, higher dispersion and better atomization. At full load, it was observed that the ignition delay is lower at higher injection pressures compared to diesel and the peak pressure is also higher. The test results show that the optimum fuel injection pressure is 240 bar. The combustion duration was almost the same at all the injection pressures. The maximum heat release takes place during the premixed combustion phase. This is attributed to the higher injection pressure, which improves atomization and mixing leading to better combustion.

10.2.4. Canola oil

Sayin et al. [101] studied the combustion characteristics of canola oil methyl ester (COME) and its blend at different injection pressures (18, 20, 22 and 24 MPa), constant engine speed and different loads on a Lombardini 6 LD 400, single cylinder, naturally aspirated, air cooled, DI diesel engine. The results showed that COME and diesel fuels

exhibit different combustion characteristics with the variation of engine load and injection pressure due to their different properties. It has been observed that COME and its blends showed shorter IDs as compared to diesel. This is attributed to the higher cetane number of biodiesel. For instance, at 25 kPa load and ORG ignition pressure the ID for B_{100} is 13.04° CA, while the ID in the case of B_0 is 14.89° CA. The results of maximum cylinder gas pressure (MGP) showed that the MGP for diesel fuel was higher at all tests. This is attributed to the high viscosity and low volatility of the biodiesel which lead to poor atomization and air–fuel mixture preparation with air during the ID period. The rates of heat release (ROHR) are lower for COME and its blends with diesel fuel. This is because the premixed heat release phase of COME was shorter than petroleum diesel. At 25 kPa, the maximum obtained ROHR for B_0, B_5, B_{20}, B_{50} and B_{100} was 25.33 (at 5.18° CA BTDC), 24.65 (at 5.51° CA BTDC), 24.05 (at 5.58° CA BTDC), 22.73 (at 5.67° CA BTDC) and 20.21 kJ/deg (at 7.16° CA BTDC), respectively. The combustion duration (CD) increased with the increase of COME amount in the fuel blend since the biodiesel continued to burn in the late combustion phase owing to high viscosity and boiling point.

10.2.5. Rapeseed oil

Ekrem [102] studied the combustion characteristics of neat rapeseed oil biodiesel and 5%, 20% and 75% by volume blends at full load condition and 2000 rpm in a six cylinders, four-stroke, turbocharged direct injection diesel engine. The test results showed that the peak cylinder pressure is decreased with the increase of rapeseed oil biodiesel addition in the blends. The peak pressures of 154.7, 150, 149, 148.5 and 147 bar were recorded for standard diesel, B_5, B_{20}, B_{70} and B_{100}, respectively. However, the combustion process of the test fuels is similar, consisting of a phase of premixed combustion following by a phase of diffusion combustion. The maximum heat release rate of standard diesel, B_5, B_{20}, B_{70} and B_{100} is 84, 79.7, 77.50, 74.9 and 72.2 J/° CA, respectively. This is attributed to the shorter ignition delay of B_{100} and its blends. For B_5, B_{20}, B_{70} blends, the heat release peak was higher than that of B_{100} due to reduced viscosity and better spray formation. The ignition delays for standard diesel, B_5, B_{20}, B_{70} and B_{100} fuels were 8.5°, 7.75°, 7.25°, 6.50° and 5.75° CA, respectively.

10.3. Impact of biodiesel from waste cooking oil on engine combustion characteristics

Mani et al. [103] evaluated the effect of four injection timings (23°, 20°, 17° and 14° bTDC) on combustion characteristics of a single cylinder, four-stroke, direct injection diesel engine operated with waste plastic oil. It has been observed that the ignition delay period and cylinder peak pressure with standard injection timing are significantly longer than that of retarded injection timing. The longer delay period with standard injection timing results in a rise in-cylinder peak pressure of 3 bar. It has also been noticed that the maximum heat release is 119 J/° CA for standard injection timing and 108 J/° CA for retarded injection timing. This indicates that the heat release rate is decreased while retarding the injection timing.

Ozesen et al. [104] studied the combustion characteristics of a diesel engine fueled with waste (frying) palm oil methyl ester (WPOME) and canola oil methyl ester (COME) at constant speed (1500 rpm) and a full load condition. The maximum cylinder gas pressures of the biodiesels are higher than that of the PBDF due to biodiesels' higher bsfc amounts, cetane number, boiling point, oxygen content, and advance in the start of injection (SOI) timing. The peak cylinder gas pressure for WPOME and COME was measured 8.34 MPa and 8.33 MPa, respectively, at 6.75° CA ATDC, while the peak cylinder gas pressure for PBDF was 7.89 MPa occurring at 7° CA ATDC. These values show that the peak cylinder gas pressure did not show any significant differences between both WPOME and COME and was 0.45 MPa higher and occurred 0.25° CA earlier than those of PBDF. The ignition delay slightly decreased with the use of biodiesels due to the higher cetane number of biodiesel which makes auto-ignition easily and gives short ignition delay. The ignition delays for WPOME, COME and PBDF were calculated 7.50°, 8.00° and 8.25° CA, respectively. The starts of combustion (SOC) timing for biodiesel are earlier than PBDF due to its earlier SOI timings. The SOC timing of the WPOME and COME was taken place at 9.75° CA before top dead center (BTDC), while the SOC timing in the case of PBDF was occurring at 7.25° CA BTDC. This value shows that the SOC timing with the use of the biodiesels advanced more than 2° CA compared to PBDF.

Muralidharan and Vasudevan [105] studied the combustion characteristics of waste cooking oil methyl ester (WCO) and it blends (B_{20}–B_{40}) in a single cylinder four-stroke variable compression ratio multi-fuel diesel engine at a fixed engine speed of 1500 rpm, 50% load and different compression ratios (18:1, 19:1, 20:1, 21:1 and 22:1). The results indicate that the combustion pressure for diesel is higher at lower compression ratios and the combustion pressure for blends is higher at higher compression ratios. The maximum rate of increase in pressure is increasing with the increase in the compression ratio. Moreover, the heat release rate of standard diesel is higher than oil blend due to its reduced viscosity and better spray formation. The heat release rate increases with the lower compression ratios and slightly decreases at higher compression ratios. The heat release rate of waste cooking oil blends decreases compared to diesel for increase in compression ratios. This may be due to the reduction in viscosity and good spray formation with increase in compression ratio in the engine cylinder.

10.4. Factors affecting the engine combustion characteristics

Mostly engine combustion characteristics are affected by the following factors: Biodiesel feedstocks (sources), contents of biodiesel, cetane number, advance injection timing and combustion, oxygen contents, engine load, engine speed, density and viscosity. Summary of the reports from various authors regarding the factors which affect the combustion characteristics of the engine have been presented in Table 13.

Table 13
Factors affecting the engine combustion characteristics.

Factors	References
Biodiesel feedstocks	[106–119]
Contents of biodiesel	[115,116,119–137]
Higher cetane number	[107,110,119,127,138–142]
Advance injection timing	[107,111,115,119,130,143–145]
Higher oxygen contents	[124,146–150]
Engine load	[102,107,115,120,122,123,128,141,147,151–157]
Engine speed	[109,114,140,153,158,159]

11. Conclusions

Biodiesel which is produced from renewable and often domestic sources represents a more potential energy source and will therefore play an increasingly significant role in solving the energy security issue along with air pollution problem. This paper aims to discuss the impact biodiesel from various feedstocks on combustion characteristics. Moreover, some significant aspects such as biodiesel development, biodiesel feedstocks, biodiesel standards, advantages and challenges of biodiesel, material compatibility and

durability were also reviewed. According to the analysis of the above literature following summery can be drawn:

- The accessibility of biodiesel feedstocks (identified as more than 350 oil-bearing crops) is one of the main reasons that make biodiesel production more convenient as an energy substitute.
- The properties of biodiesel must meet the ASTM D6751 and EN 14211 standards to be used in engines.
- Vegetable oil cannot be used directly in diesel engines due to their higher viscosity, low volatility and polyunsaturated characteristics. Therefore, these problems can be overcome by four methods: pyrolysis, dilution with hydrocarbons blending, micro-emulsion, and transesterification. Transesterification process is the best method among all process.
- Biodiesel has a tendency to dissolve the accumulated particulates and sediments found in diesel storage and engine fuel systems. These dissolved sediments may plug fuel filters or injectors. Biodiesel may also degrade some hoses, gaskets, O-rings, seals elastomers, glues and plastics with prolonged exposure. Therefore, the following materials were recommend for biodiesel as follow:
  - Teflon
  - Viton
  - Fluorinated plastics
  - Nylon
  - Aluminum
  - Carbon, stainless steel
  - Fiberglass (most types)
- During the engine durability test, many authors reported that lower carbon deposit and wear were observed in automotive components. While very few authors reported similar or higher carbon deposit.
- Most of the results showed that biodiesel from edible and non-edible oil feedstocks has lower peak cylinder pressure and lower heat release rate compared to diesel fuel. This is attributed to the higher cetane number of biodiesel resulting in shorter ignition delay and more fuel burnt in diffusion stage. Moreover, the improper mixing of biodiesel with air due to higher viscosity and lower calorific value is another cause.

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